NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 4263

EFFECT OF PRIOR AIR FORCE OVERTEMPERATURE OPERATION ON LIFE OF J47 BUCKETS EVALUATED IN A SEA-LEVEL CYCLIC ENGINE TEST

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Lewis Flight Propulsion Laboratory
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SUMMARY

Buckets of S-816 alloy removed from two J47 engines overtemperatured in service operation were evaluated in laboratory and engine tests. Some buckets were tested in the as-overtemperatured condition while others were heat-treated prior to testing. Heat treatments were performed to find their effect on recovery of bucket life. Buckets were operated in a J47-25 engine for cycles of 15 minutes at rated speed and 5 minutes at idle speed.

Engine results indicated that overtemperatured buckets did not fracture in abnormally short operating times. Cracking, particularly on the leading edge, was the principal mode of failure of buckets. Cracks developed after short operating times but did not propagate to fracture during several hundred hours of operation. The as-overtemperatured bucket groups developed leading-edge cracks in a higher percentage of buckets than did the standard group, but this may have been the result of prior service at normal conditions, overtemperature operation, or both. Buckets did not fail by a stress-rupture mechanism in this engine, but tests were performed to determine the effect of overtemperature on rupture properties and the effect of heat treatment on recovery of properties. Stress-rupture life of specimens cut from as-overtemperatured buckets was shorter than the life of specimens from standard buckets. Full reheat treatment of overtemperatured buckets using the standard heat treatment increased resistance to leading-edge cracking and improved stress-rupture life, compared with the as-overtemperatured groups; the performance of these buckets in the engine test and the life in stress-rupture tests were about equivalent to results obtained for new standard Air Force stock buckets. Reaging of overtemperatured buckets did not improve performance in the engine or life in the stress-rupture test.

INTRODUCTION

Turbojet engines operated in service are sometimes overheated or "overtemperatured." Overtemperature operation may be defined as operation at temperatures greater than an allowable maximum operating temperature.

The component of primary concern in turbojet engines is the turbine bucket, which operates under the most severe combination of stress, temperature, and corrosive atmosphere. Any abnormal temperature condition, such as an overtemperature, might drastically reduce bucket life. Several examples of overtemperature conditions during service operation are shown in table I. It is evident from the conditions listed in the table that bucket stresses may be high or low, temperatures may range from slightly above normal to melting temperature, and times may range from a few seconds to several hours. Since the conditions of overtemperature vary considerably in service, the effect of overtemperature on bucket life may be expected to vary. 4567

Severely overtemperatured buckets that are melted, cracked, warped, or elongated greatly are easily detected during routine field and overhaul inspection and may be discarded. However, most buckets that are thought, or known, to have been overtemperatured display no visible external evidence of such overtemperature. In these cases, it has been necessary for the Air Force to rely on pilot observations, maintenance records, and microstructural examinations to classify buckets as overtemperatured. Microstructural examinations are performed on sections cut from buckets suspected of having been overtemperatured. Although it has been shown that the evidence is not always reliable (ref. 1), spheroidization or solution of precipitates have been taken as indications of overtemperature operation. The investigation of reference 1 showed that microstructures of some new buckets were similar to microstructures found in all but severely overtemperatured buckets. Other investigations pertaining to overtemperature problems have been conducted by the U.S. Air Force, manufactures, and NACA Lewis laboratory. Investigations have shown that the stress-rupture life of some bucket materials was reduced in laboratory tests simulating overtemperature conditions (refs. 2 and 3). In an investigation conducted at the NACA Lewis laboratory (ref. 4), buckets of S-816 alloy were heated to different temperatures and subsequently operated in a J33 turbojet engine. Results indicated no loss in life of these S-816 buckets due to the treatments simulating overtemperature, but there was some evidence that stress-rupture properties of the material were reduced by overtemperature.

The purpose of this investigation was to obtain additional insight into the effect of overtemperature on the life of turbine buckets. Also, the effect of various heat treatments on the life of overtemperatured buckets was studied to determine whether reheat treatment recovered properties that may have been lost by overtemperaturing.

Buckets of S-816 alloy, removed from two engines overtemperatured in service, were used in this investigation. Some of the buckets were tested in the as-overtemperatured condition, while others were heat-treated prior to testing. The buckets were installed in a J47-25 engine and were operated for repeated cycles of 15 minutes at rated speed (7950 rpm) and 5 minutes at idle speed (3000 rpm). Stress-rupture tests and metallographic examinations were made in an attempt to correlate properties and microstructures with the engine results.

MATERIALS AND PROCEDURE

Buckets

The turbine buckets studied in this investigation were forged S-816 (AMS-5765A) alloy. The nominal chemical composition of the alloy is shown in the following table:

Element	C	Co	Cr	Ni	Mo	W	Cb	Fe	Mn
Percent by weight	0.4	43.7	20	20	4	4	4	2.8	1.0

Buckets from two engines that had undergone overtemperature operation in service were submitted by the Air Force to the NACA Lewis laboratory for study. These buckets were selected as typical examples of service overtemperatured buckets. Information describing some of the service history of the engines from which the buckets were removed is shown in the following table:

Engine designation	Aircraft	Engine model	Hours operated	Overtemperature conditions
A[a]	B47-B	J47-11	209	Tailpipe temperature over 1800° F (about 500° over normal) on acceleration.
B	F86	J47-13	242	Engine overspeed of 104 percent with tailpipe temperature over 1500° F. (about 200° over normal) for unknown length of time.

[a]Engines are arbitrarily designated as engines A and B for reference throughout this report.

Condition of Turbine Buckets

Half of the buckets from each engine were received in the as-overtemperatured condition. The remaining buckets from each engine were heat-treated at the Air Force overhaul depot in a reducing atmosphere of cracked city gas; half of these buckets from each engine were fully reheat-treated (solution-treated, $1\frac{1}{2}$ hr at 2150° F and water-quenched, aged 16 hr at 1600° F and air-cooled). Half of these buckets from each engine were aged only (16 hr at 1400° F and air-cooled). Fifteen of the as-overtemperatured turbine buckets from each engine were fully heat-treated at the Lewis laboratory by using the same temperatures and times listed previously. In this case, an inert atmosphere of argon gas was used. The heat treatments were performed in an attempt to recover properties that may have been lost by overtemperaturing.

Inspection. - Prior to evaluation in the engine test, all buckets were examined for cracks and flaws, and all buckets were found to be defect free.

Engine-tested buckets. - Buckets were selected for engine testing from the as-overtemperatured and heat-treated groups mentioned previously. In addition, new buckets in the standard heat-treated condition (2150° F for 1 hr and water-quenched, 1400° F for 16 hr and air-cooled) were included in the engine test as a standard for comparison. Table II lists the buckets that were inserted at the start of the engine test.

Engine Operation

Nine groups of buckets were installed in a J47-25 engine and were operated for repeated cycles of 15 minutes at rated speed (7950 rpm) and about 5 minutes at idle speed (3000 rpm). Only the time at rated speed is considered in the discussion of bucket life.

Bucket stress and temperature were controlled by adjusting the engine speed and exhaust nozzle area, respectively. Temperature measurements of buckets were made by using themocouples installed at midspan in each of two buckets. Temperature readings were transmitted through sliprings to a recording potentiometer (ref. 5).

Stress and temperature distribution in buckets. - Centrifugal stress and temperature distributions in bucket airfoils are shown in figure 1. The centrifugal stress was calculated using cross-sectional areas, density, and rotational speed (ref. 6). The temperature distribution shown in figure 1 was obtained before the engine test was started. To do this, the turbine wheel was fully bucketed with standard Air Force stock buckets, and the engine was operated for a sufficient time to obtain equilibrium condition at full power. Temperature measurements were obtained from thermocouples imbedded in four of the turbine buckets.

Bucket elongation measurements. - Two buckets of each group were scribed for elongation measurements, as shown in figure 2. Elongation readings were taken of the scribed zones during frequent shutdowns. The measurements were made with an optical extensometer and were sensitive to about ±0.4 percent in the 1/2-inch gage length.

Macroexamination of buckets. - Buckets were examined for cracks, using post-emulsifying zyglo, after intervals of about 40 hours of rated-speed operation. The cracks were classified (fig. 3) as follows: (1)
4567 leading edge, (2) radial tip, and (3) trailing-edge tip. To follow the progression of cracks, photos were taken of a sample of about 20 cracked buckets after the 198-hour inspection and after every subsequent inspection. A double exposure was taken of the cracked buckets; the first exposure used an ultra-violet light to define the cracks, and a normal flash was used to show the entire bucket.

Metallographic Studies

Two untested buckets from each of the bucket groups listed in table I were sectioned for metallographic examination. In addition, metallographic examinations were made of engine-tested buckets of each group except groups 4 and 8. Groups 4 and 8 were not examined because they were equivalent to groups 2 and 6 except in the atmosphere used for the heat treatment. Photomicrographs were taken to illustrate typical microstructures and typical cracks in buckets.

Stress-Rupture Tests

Stress-rupture tests were performed on specimens from all groups of buckets listed in table II to correlate properties with microstructure and engine performance. Test bars were cut from the airfoils of three buckets of each group, with the exception of the standard S-816 group, from which six test specimens were obtained. The tests were performed at 1500° F and 23,600 pounds per square inch.

RESULTS

Engine Results

Bucket failures. - Only one bucket had fractured when the test was discontinued after 660 hours at rated speed. The fracture occurred in an overtemperatured and reaged bucket (group 3) after 652 hours of operation. However, 81 buckets (84 percent) were cracked at the conclusion of the test after 660 hours (table III). Cracked buckets were first detected in the second zyglo inspection, which was performed after 80 hours. With the exception of the three buckets with trailing-edge tip cracks, all buckets were reinserted in the engine after zyglo inspection, and the test was continued to determine the rate of crack propagation.

It should be noted that all cracked buckets are removed from service by the Air Force, since they are considered to be "failed" buckets.

Buckets ran for long periods of time without fracture after the inception of cracks. The one bucket that fractured ran 572 hours from the time cracks were first noted until it fractured. Photos of some of the buckets showing the progression of cracks during the course of the test are presented in figure 4. The depth of cracks did not increase very rapidly, as shown in figures 4(a) and (b), which illustrate the cracks after 198 and 500 hours of operation, respectively. After 500 hours, the largest leading-edge crack in bucket 81 elongated more rapidly (figs. 4(c) and (d)) and the bucket fractured in 652 hours (fig. 4(e)). The cracks in the other three buckets shown are relatively short after 660 hours, when the test was concluded (fig. 4(f)). 4567

Leading-edge cracking. - The leading-edge cracking data have been plotted in figure 5. Figure 5(a) shows the cumulative percentages of buckets with leading-edge cracks for each of the groups of buckets originally obtained from engine A (groups 1 to 4). The percentages of buckets with leading-edge cracks is plotted against engine test time. Figure 5(b) shows similar data for the groups of buckets originally obtained from engine B (groups 5 to 8). For comparison, both figures show leading-edge cracking data for the standard Air Force stock buckets (group 9). Buckets of the as-overtemperatured groups (1 and 5) and the overtemperatured and reaged groups (3 and 7) developed leading-edge cracks more readily than buckets in the other groups. After 240 hours of operation, leading-edge cracks were present in 60 percent of the buckets of groups 1 and 3 and in 40 and 70 percent, respectively, of buckets of groups 5 and 7 (fig. 5). Only 18 percent of the standard Air Force stock buckets (group 9) had leading-edge cracks after 240 hours. However, the group 9 buckets were new when they were installed in the engine test, while all other groups had a prior service life. The service life of the buckets is not known, but the flight time on the engines was 209 and 242 hours, respectively, for engines A and B. Perhaps the prior service life, rather than overtemperature, accounts for the larger number of leading-edge cracked buckets.

The overtemperatured and reheat-treated buckets (groups 2, 4, 6, and 8) had less tendency to form leading-edge cracks than the buckets of the as-overtemperatured groups and the overtemperatured and aged groups. The incidence of leading-edge cracking in groups 2, 4, 6, and 8 was similar to that in group 9, the standard buckets. Group 2 had a large number of buckets (50 percent) with leading-edge cracks after 80 hours but had no additional leading-edge cracked buckets until 480 hours. Thus, the reheat treatment recovered at least a portion of the resistance to leading-edge cracking that the as-overtemperatured buckets lost from service life or from overtemperature operation.

Radial-tip cracking. - The incidence of radial-tip cracking is shown in figure 6. The difference between the bucket groups in the incidence of radial-tip cracking was less than that obtained for leading-edge

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cracking. The data in figure 6(a) show little difference in incidence of radial-tip cracking among bucket groups from engine A. Upon first examination of figure 6(b), however, there might appear to be a significant difference in the incidence of radial-tip cracking among bucket groups from engine B. Particularly, it would appear that the group given a full reheat treatment by the Air Force (group 6) has a greater incidence of tip cracking than does the group given the full reheat treatment by the NACA (group 8). The noted difference is not believed to be significant, however, since, in the case of the similar groups of engine A (groups 2 and 4) no detrimental effect of the Air Force treatment was noted; and, even in the case of the previously discussed leading-edge cracking (fig. 5(b)), the effect of the full reheat treatment was about the same, whether given by the Air Force (group 6) or NACA (group 8).

The effect of reaging alone on radial-tip cracking was not consistent among the bucket groups from the two engines. The overtemperatured and reaged buckets of engine A (group 3) had a relatively high incidence of radial-tip cracking, while the equivalent group from engine B (group 7) had a low incidence. In general, it is felt that no consistent relation has been found between reheat treatment and incidence of radial-tip cracking, and reheat treatment has not been found to be beneficial in reducing the incidence of tip cracking.

Bucket elongation. - Elongation measurements taken on two buckets of each group showed a maximum elongation of about 0.6 percent in a 1/2-inch gage length. However, the scatter in data was about ±0.4 percent, so elongation was almost within experimental error and may be considered negligible.

Metallographic and Stress-Rupture Studies

Untested buckets. - Typical microstructures of bucket from the overtemperatured groups and the standard group before engine testing are shown in figure 7. The standard heat-treated S-816 alloy bucket (fig. 7(a)) has large, stable, columbium-tantalum carbide precipitates in the matrix and continuous grain-boundary precipitation. The as-overtemperatured bucket microstructures (groups 1 and 5) in figure 7(b) show agglomeration and spheroidization of grain-boundary precipitates that have been associated with overtemperature, as described earlier. Although the photomicrographs of the specific buckets of figure 7(b) indicate slightly more hyphenation of grain-boundary precipitation for group 1 than for group 5, examination of microstructures of a number of buckets from groups 1 and 5 indicates that the degree of hyphenation is about equivalent for the two groups of buckets. Buckets of groups 2, 4, 6, and 8, overtemperatured and reheat-treated, are shown in figures 7(c) and (e). The microstructures are typical of S-816 in the normal heat-treated condition. The microstructural evidence associated with overtemperature is no longer visible. The overtemperatured and reaged buckets of groups 3 and 7 are shown by the microstructures in figure 7(d). The precipitation has become slightly more agglomerated and spheroidized than that in the as-overtemperatured buckets.

Engine-tested buckets. - Microstructural studies of buckets after engine testing are presented in figure 8. Buckets of all groups showed an advanced stage of aging, with little or no microstructural difference among groups. Several small leading-edge cracks are also shown in the photomicrographs. Small cracks with less oxidation than the larger cracks were photographed because oxidation obscured the surfaces of larger cracks and hampered classification of cracks as intergranular or transgranular. 4567

In addition to the continuous cracks near the leading edge, there were clusters of voids present in the grain boundaries of buckets. The voids were found in buckets from every group, but only specimens from the as-overtemperatured and the standard groups are shown in figure 9. The voids are in the grain boundaries transverse to the direction of centrifugal stress in the airfoil. They are found near, but not at, the leading edge and extend inward for a distance of about 0.2 inch.

The fracture surface of the one bucket that fractured in this investigation is shown in figure 10. The fracture surface is near the leading edge where failure began and at a point near the center of the chord length. The fracture appears intergranular near the leading edge and transgranular near midchord. The failure was propagated by fatigue from a leading-edge crack until the load-carrying area was reduced sufficiently to cause tensile failure.

A typical radial-tip crack shown in figure 10 is a transgranular fatigue failure. Buckets ran for 500 hours with such radial-tip cracks and did not fracture.

Stress-rupture results. - Stress-rupture lives of specimens cut from the airfoil of buckets of each group are shown in figure 11. All specimens were tested at 1500° F and 23,600 pounds per square inch, which are the conditions for a nominal life of 100 hours for standard S-816 alloy bar stock. Stress and temperature conditions in a range corresponding to that in buckets during the engine test were not used, since the life of specimens would have been too long. For example, at a point 2 inches above the base of the airfoil, which is in the zone where stress-rupture life of buckets is at a minimum, bucket centrifugal stress is about 10,400 pounds per square inch and bucket temperature is about 1470° F (fig. 1). Stress-rupture life at these conditions is of the order of 30,000 hours for S-816. The mean stress-rupture life of specimens from standard S-816 buckets was 94 hours, which is reasonably close to the nominal 100-hour life for bar stock. The as-overtemperatured groups had shorter stress-rupture lives than the standard group, with mean lives of 54 and 64 hours for groups 1 and 5, respectively. The test bars from the fully reheat-treated groups showed an improvement in life over the as-overtemperatured group bars; this indicated some recovery of stress-rupture properties. The mean lives of 86, 130, 94, and 88 hours are about equivalent to the standard group. The as-overtemperatured and reaged groups did not show recovery of properties; mean lives were 52 and 77 hours, which are equivalent to the lives of the as-overtemperatured groups.

DISCUSSION

Bucket Performance

The engine test was discontinued after 660 hours of test, because sufficient data had been obtained to indicate that overtemperatured buckets had not fractured in abnormally short operating times. Only one out of 80 overtemperatured buckets had fractured in 660 hours, and this fracture occurred after 652 hours.

Cracking, particularly on the leading edge, was the most prevalent mode of bucket failure in this investigation. While only one bucket fractured during the course of the test, 81 buckets or 84 percent of all the buckets had developed leading-edge or radial-tip cracks. Cracks in buckets were detected early in the test, but the cracked buckets ran for long times without fracture. The one bucket that fractured had a time differential of about 570 hours from inception of cracking to fracture. Also about 50 percent of the as-overtemperatured buckets had run more than 400 hours after developing cracks. A long life between cracking and bucket fracture, as obtained in this engine test, is particularly desirable since it would permit cracked buckets to be found during regular inspections and replaced before fracture could cause catastrophic failure. Of course, the life between cracking and fracture for service life must be determined for service conditions before a reasonable inspection interval can be selected.

Since leading-edge cracking was the principal mode of failure, the number of buckets in each group with leading-edge cracks was compared in order to evaluate the performance of the various groups. The as-overtemperatured groups (1 and 5) had a greater number of leading-edge cracked buckets than the standard bucket group (9, fig. 5). However, the standard buckets were new when inserted in this test, while the as-overtemperatured buckets had been in service for some time in addition to having been subjected to an overtemperature condition. The higher incidence of leading-edge cracking in the as-overtemperatured groups may have been caused by the effects of prior service life alone, overtemperature alone, or a combination of both.

To understand how prior service life may cause the higher incidence of leading-edge cracking, it is necessary to indicate the engine operating conditions most directly associated with leading-edge cracking. Unpublished results obtained at this laboratory in another series of engine tests have indicated that leading-edge cracking in the J47 engine is a thermal fatigue failure associated with the thermal stresses developed primarily during starting and stopping the engine. The number of starts and stops the buckets have been subjected to during prior service may have had a much more important effect on the time to cracking than the overtemperature operation. It is impossible to separate the effects of prior service life and overtemperature operation on leading-edge cracking in this investigation on the basis of the data available.

In this investigation, resistance to leading-edge cracking appears to have been increased by the full standard heat treatment of as-overtemperatured buckets. As may be noted in figure 5, groups 2, 4, 6, and 8 had lower incidences of leading-edge cracking than did the as-overtemperatured groups, 1 and 5. In fact, the incidence of leading-edge cracking of the fully reheat-treated groups was about the same as the new standard-group buckets.

The reaging treatment, without a prior solution treatment, did not improve crack resistance of the overtemperatured buckets. The overtemperatured and reaged groups (3 and 7) cracked at about the same rate as the as-overtemperatured groups.

Radial-tip cracks that developed in a number of buckets were the secondary mode of failure in this investigation. Radial-tip cracks are attributed to vibratory fatigue and generally are not associated with overtemperature. The trailing-edge tip of the bucket, where this crack occurs, undergoes relatively little temperature change compared with the midspan portion of the bucket during overtemperature; and any overtemperature effects would probably be much less severe.

As noted in the results, the stress-rupture properties of the various groups differed appreciably. The stress-rupture life of specimens from as-overtemperatured buckets and overtemperatured and aged buckets was lower than that of standard-bucket specimens (fig. 11). This might be expected because overtemperature exposure can reduce stress-rupture properties of S-816 alloy, as has been shown in the laboratory and engine studies (refs. 2 and 3).

While the stress-rupture properties of specimens cut from overtemperatured buckets were lower than new buckets, buckets were not fractured in the engine test by a stress-rupture mechanism. This is not surprising since J-47 bucket centrifugal stresses are relatively low and stress rupture is usually not the primary mode of bucket failure in this engine The stress-rupture life of J47 buckets of S-816 alloy, if failure results solely from centrifugal stress and temperature at rated-speed conditions, is of the order of 30,000 hours. In NACA engine tests, J47-bucket life has been shown to be relatively insensitive to the stress-rupture strength of the bucket material. A reduction in rupture properties similar to that obtained in the as-overtemperatured buckets of this program would probably lead to early bucket fractures in an engine where stress rupture is an important failure mechanism.

The overtemperature exposure in these studies may be considered an overaging treatment that exhausted some of the capacity for precipitation strengthening during engine operation. The buckets in this investigation appeared to have been overaged and thus would be expected to have a lower stress-rupture life. It also follows that the reaging treatment given to overtemperatured buckets (groups 3 and 7) would not improve stress-rupture life. However, the reaging treatment did not cause a further reduction in life because it did not appreciably change the degree of overaging in the buckets.

While overtemperature may and usually does cause a reduction in stress-rupture life, it does not do so in all cases. Solution temperatures are sometimes reached during overtemperature, and the solution and reprecipitation of strengthening minor phases during subsequent normal operation may improve rather than reduce subsequent stress-rupture life (refs. 1 and 3). The improvement in life with these high-temperature conditions is most likely when the stress level is very low such as in a hot start. Obviously, high stress accompanying solution temperature conditions would lead to a high creep rate and early fracture.

Reheat treatment of overtemperatured buckets in this investigation improved the stress-rupture life of specimens, compared with those taken from as-overtemperatured buckets. In fact, the life of fully reheat-treated buckets was about the same as the life of specimens from new standard Air Force stock buckets. Resolution of the overaged precipitates and subsequent reprecipitation as a fine uniformly dispersed phase are believed to have recovered stress-rupture life. Recovery of stress-rupture life does not mean that properties lost from overtemperature can be recovered in all cases. Thermal effects of overtemperature on rupture life in form of overaging may be recovered, but it is very likely that creep or strain effects cannot be recovered. In a relatively low stress engine, such as the J47, almost negligible creep results in normal service life at or below standard operating conditions; negligible creep was obtained in this investigation in over 600 hours of operation at rated speed. However, creep occurs when overtemperature is accompanied by high stress in buckets, and in these cases rupture properties very likely would not be recoverable for this alloy.

As indicated in the results, clusters of voids were observed in the examination of microstructures after engine testing (fig. 10). The voids do not appear to be intergranular oxidation or rupture tears may be evidence supporting a theory that intergranular failure of metals at higher temperatures is caused by migration and collection of interstitial gases or vacant lattice sites, as suggested by Parker in 1944 (ref. 7) and others more recently (ref. 8). These voids have been seen in rupture specimens by others (refs. 9 and 10) and may be associated with the failure mechanism of leading-edge cracks.

SUMMARY OF RESULTS

Buckets of S-816 alloy removed from two J47 engines overtemperatured in service operation were evaluated in engine and laboratory tests. The overtemperature conditions for the two engines were reported in service records as 200° and 500° F above normal operating temperatures. Some of the buckets were tested in the as-overtemperatured condition while others were heat-treated prior to testing. A group of new buckets selected from Air Force stock was included as a standard for comparison.

The buckets were tested in a J47-25 engine operated for cycles of 15 minutes at rated speed (7950 rpm) and about 5 minutes at idle speed (3000 rpm). Although it was highly improbable that buckets would fail by stress rupture in this engine because of the relatively low centrifugal stresses, stress-rupture tests were performed to find the effect of overtemperature on rupture properties and the effect of heat treatment on recovery of these properties. 4567

The results obtained were:

1. Service overtemperatured buckets did not fracture in abnormally short operating times; only one of 80 overtemperatured buckets fractured during the 660-hour test, and that fractured after 652 hours.

2. While only one bucket fractured, 84 percent of all of buckets had leading-edge or radial-tip cracks at the conclusion of the test.

3. Cracks were first observed at the inspection after 80 hours of operation, but the cracked buckets ran for long times without fracture. The one bucket that fractured had run 572 hours from inception of a leading-edge crack to fracture. At the conclusion of the test, about 50 percent of the cracked as-overtemperatured buckets had run with leading-edge cracks at least 400 hours without fracture. The long life between cracking and fracture obtained in this test indicated the possibility that cracked buckets may be found by regular inspections and removed before a catastrophic failure results.

4. The as-overtemperatured bucket groups had a considerably higher percentage of leading-edge cracked buckets than the standard bucket group at the conclusion of the test. This may have been the result of prior service at normal conditions, overtemperature, or both.

5. Radial-tip cracking appears to be a vibratory fatigue failure and is probably little affected by overtemperature.

6. Stress-rupture life of specimens cut from airfoils of as-overtemperatured buckets were shorter than the life of specimens from standard buckets, with mean lives of 54 and 64 hours for the two as-overtemperatured groups and 94 hours for the standard group. The variation of rupture properties did not affect bucket life because stress rupture was not the primary mode of failure in this engine.

7. Reheat treatment of overtemperatured buckets using the standard heat treatment increased resistance to leading-edge cracking and recovered stress-rupture properties. Performance of these buckets in the engine test and specimens in stress-rupture were about equivalent to standard Air Force stock buckets.

8. Reaging of overtemperatured buckets did not improve performance in the engine or in rupture tests. Stress-rupture life and engine performance were approximately equivalent to that of the as-overtemperatured buckets.

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Lewis Flight Propulsion Laboratory
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TABLE I. - OPERATING CONDITIONS DURING WHICH OVER-TEMPERATURE MAY BE ENCOUNTERED

Condition	Temperature difference above normal maximum	Probable stress	Duration
Hot start	Can exceed melting temperature of buckets	Very low	Short (few sec)
Acceleration, compressor stall	Can be very great	Low	Short (few sec)
Fuel flow increased too rapidly	Moderate to great	Low to high	Short (few sec)
Afterburner ignition	Can be great	High	Short (few sec)
Drift or malfunction of thermocouples	Moderate	High	Can be long (several hr)
Very high altitudes (primarily reduced compressor efficiency)	Moderate to great	High	Moderate

TABLE II. - BUCKETS TESTED

Source	Group number	Number of buckets	Thermal condition of buckets tested
Engine A - tailpipe temperature over 1800° F (about 500° F over normal temperature)	1	10	As-overtemperatured
	2	10	Overtemperatured plus full reheat treatment by Air Force
	3	10	Overtemperatured plus aged by Air Force
	4	10	Overtemperatured plus full reheat treatment by NACA
Engine B - tailpipe temperature over 1500° F accompanied by 104 percent overspeed (about 200° F over normal temperature)	5	10	As-overtemperatured
	6	10	Overtemperatured plus full reheat treatment by Air Force
	7	10	Overtemperatured plus aged by Air Force
	8	10	Overtemperatured plus full reheat treatment by NACA
New buckets from Air Force stock	9	14	Standard heat treatment

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TABLE III. - ENGINE RESULTS; BUCKETS CRACKED

[Number of buckets is cumulative total for each column.]

Time, hr	Group number																																			
	1				2				3				4				5				6				7				8				9			
	As-overtemperatured				Reheat-treated by Air Force				Reaged by Air Force				Reheat-treated by NACA				As-overtemperatured				Reheat-treated by Air Force				Reaged by Air Force				Reheat-treated by NACA				Standard Air Force stock			
	LE[a]	RT[b]	TET[c]	RT + LE[d]	LE	RT	TET	RT + LE	LE	RT	TET	RT + LE	LE	RT	TET	RT + LE	LE	RT	TET	RT + LE	LE	RT	TET	RT + LE	LE	RT	TET	RT + LE	LE	RT	TET	RT + LE	LE	RT	TET	RT + LE
40																																				
80									3					1									[e]2													
109	2				6																	1	2													
148																	1	1				1	3							1						
198									4			1										1	3	1	2											
240	6								5			1					4	1							6			1	1	1			3	1		
290	8								7			1	3	1			6	2				2	3	1	7			1					5	2		
332	7			1					6			2					5	3							8			1	1	2						
372	7	1		1									2	1		1	4	3		1		3	3	1									3	3		
417	8	1		2					7			2													9			1					7	3		
457	7	1		2									3	1		1						3	3	1									7	3		1
500					5			1	6			3	4	1		1																				
540					6			1									6	3		1	2	3	3	1												
580													6	1		1	5	2		2	2	3	3	1									8	3		1
620	7			3													6	2		2	3	3	3	1					4	2			8	2		2
652																																				
660	7			3	6			1	6			3	6	1		1	6	2		2	3	3	3	1	9			1	4	2			8	2		2

[a]LE, leading-edge cracks

[b]RT, radial-tip cracks

[c]TET, trailing-edge-tip cracks

[d]RT + LE, both radial-tip and leading-edge cracks

[e]Buckets removed

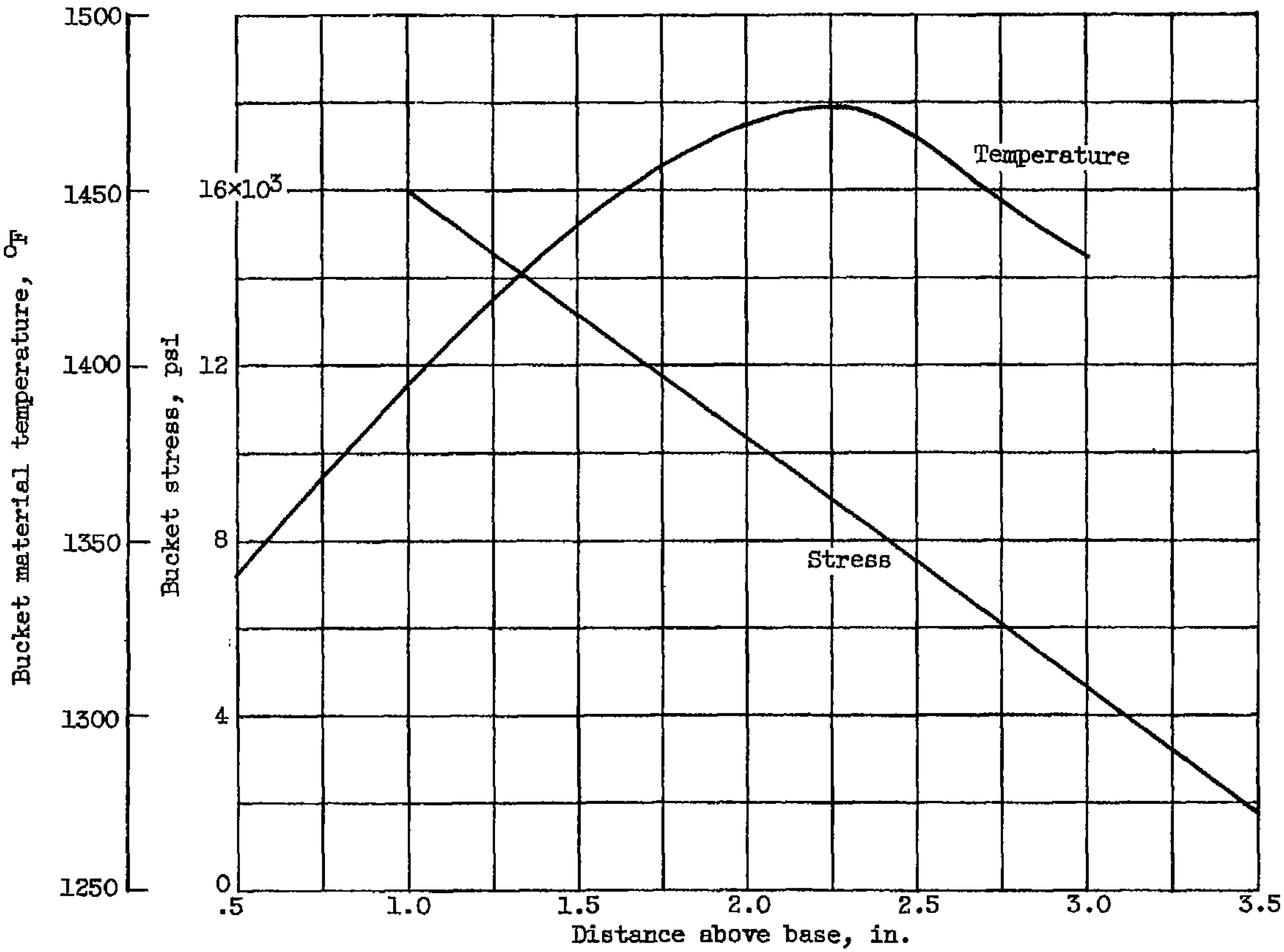


Figure 1. - Distributions of centrifugal stress and bucket temperature in J47 turbine bucket.

4567

CO-3 back

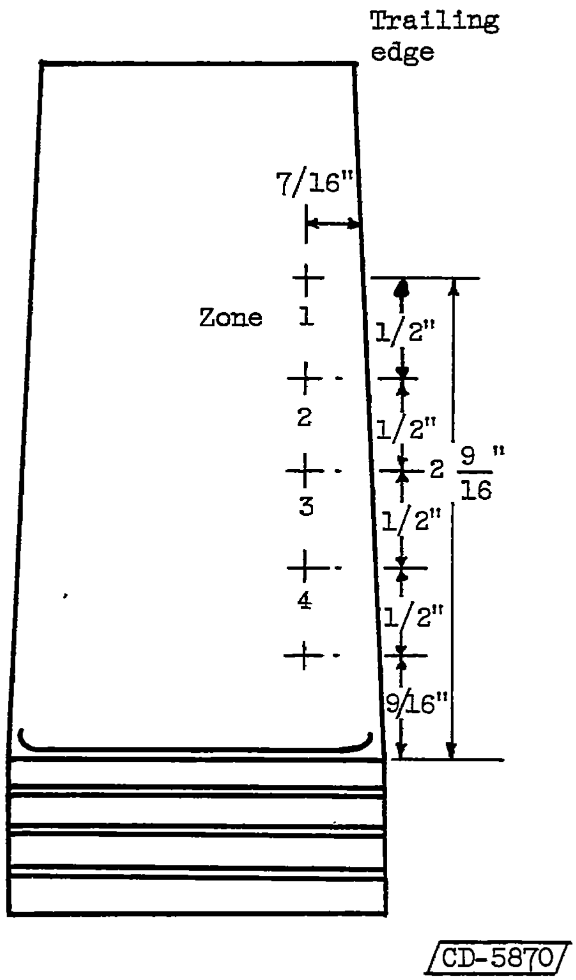


Figure 2. - Scribed marks for elongation measurements.

4567

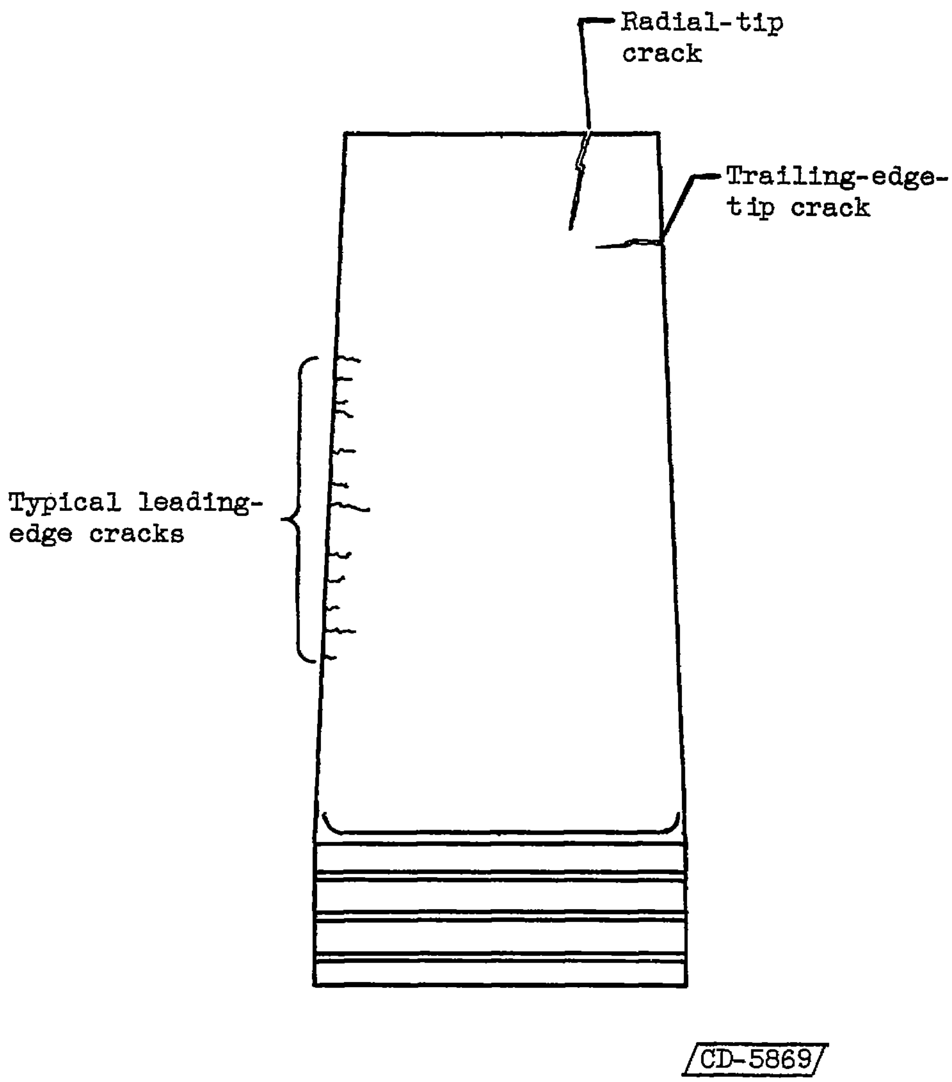
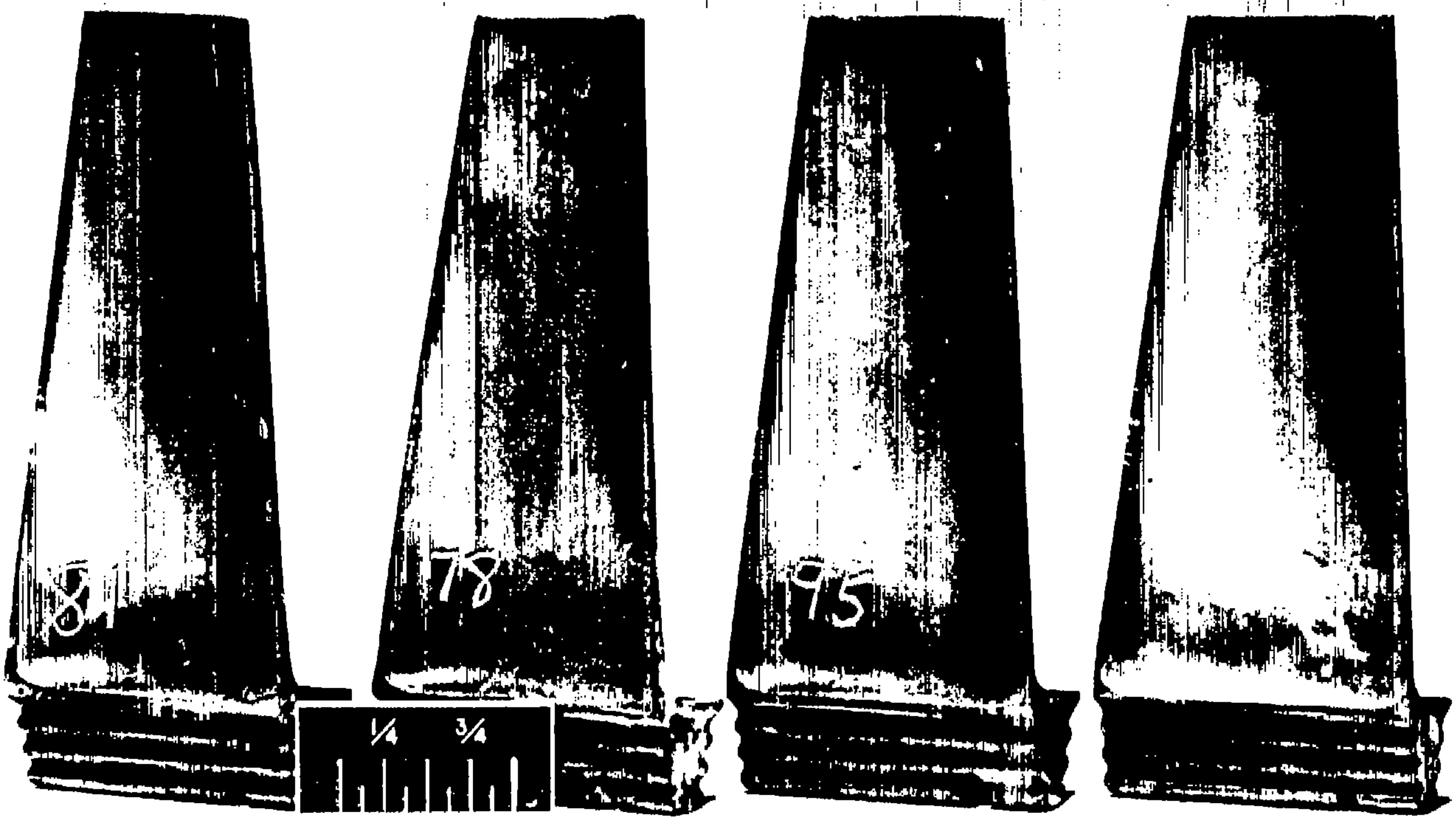


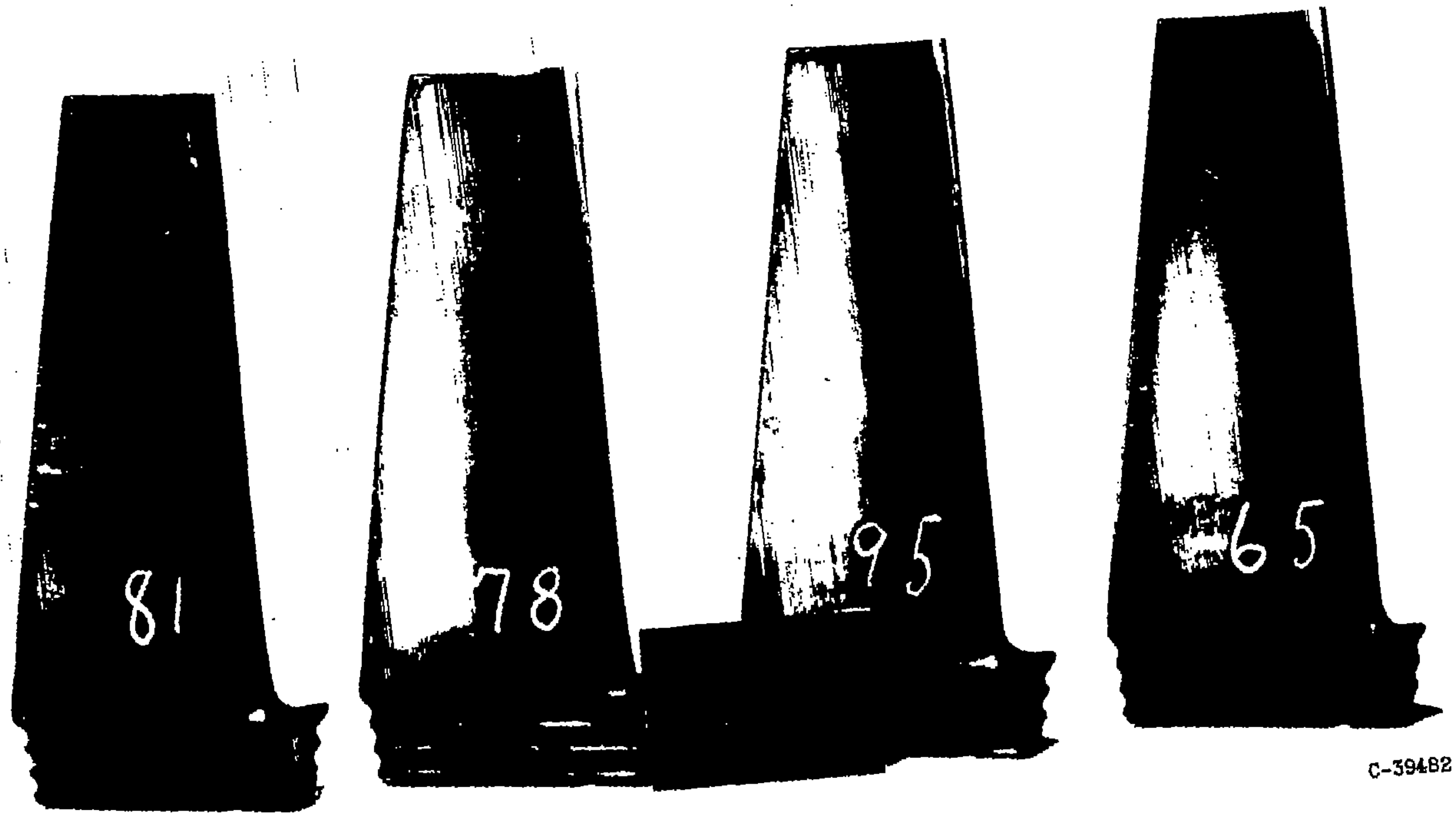
Figure 3. - Crack classification.



C-37812

(a) Inspection, 198 hours.

Figure 4. - Progression of cracks in representative buckets.



C-39482

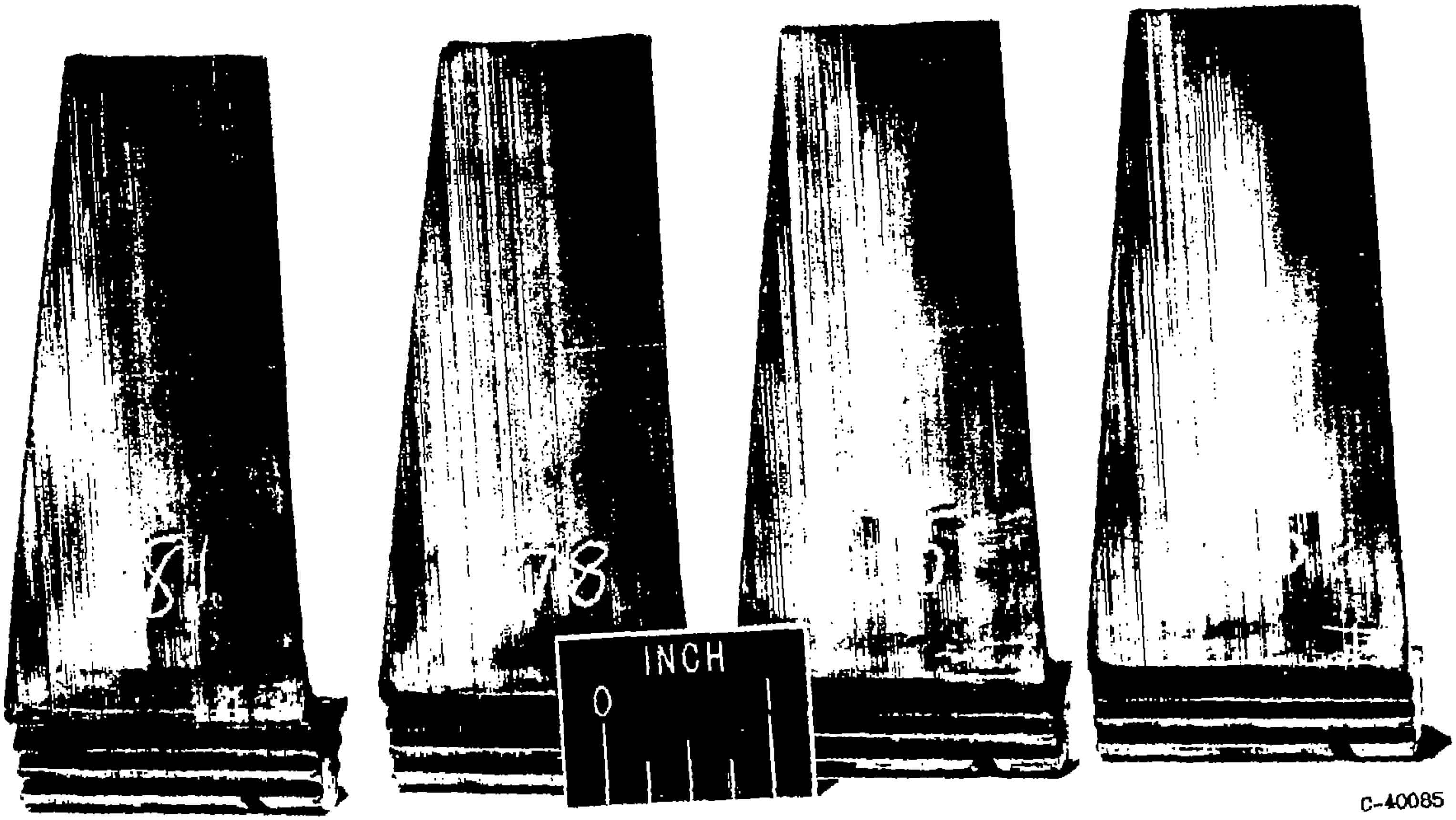
(b) Inspection, 500 hours.

Figure 4. - Continued. Progression of cracks in representative buckets.

C-39841

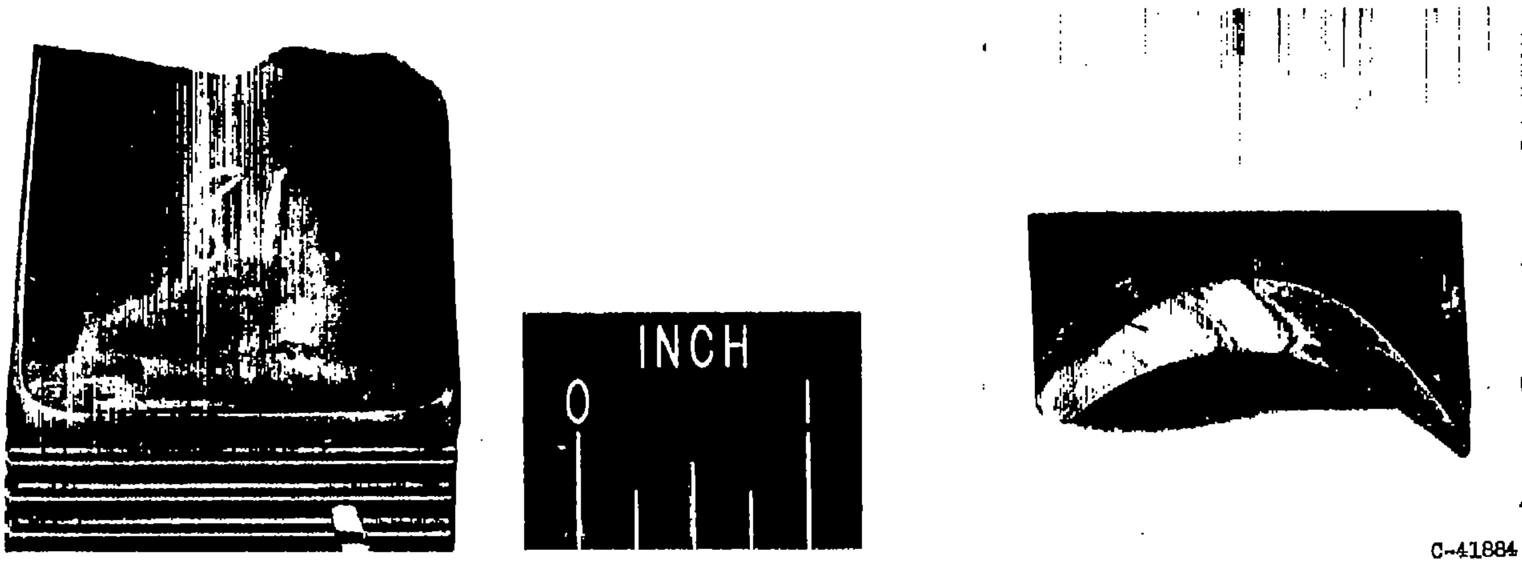
(c) Inspection, 580 hours.

Figure 4. - Continued. Progression of cracks in representative buckets.



(d) Inspection, 620 hours.

Figure 4. - Continued. Progression of cracks in representative buckets.



C-41884

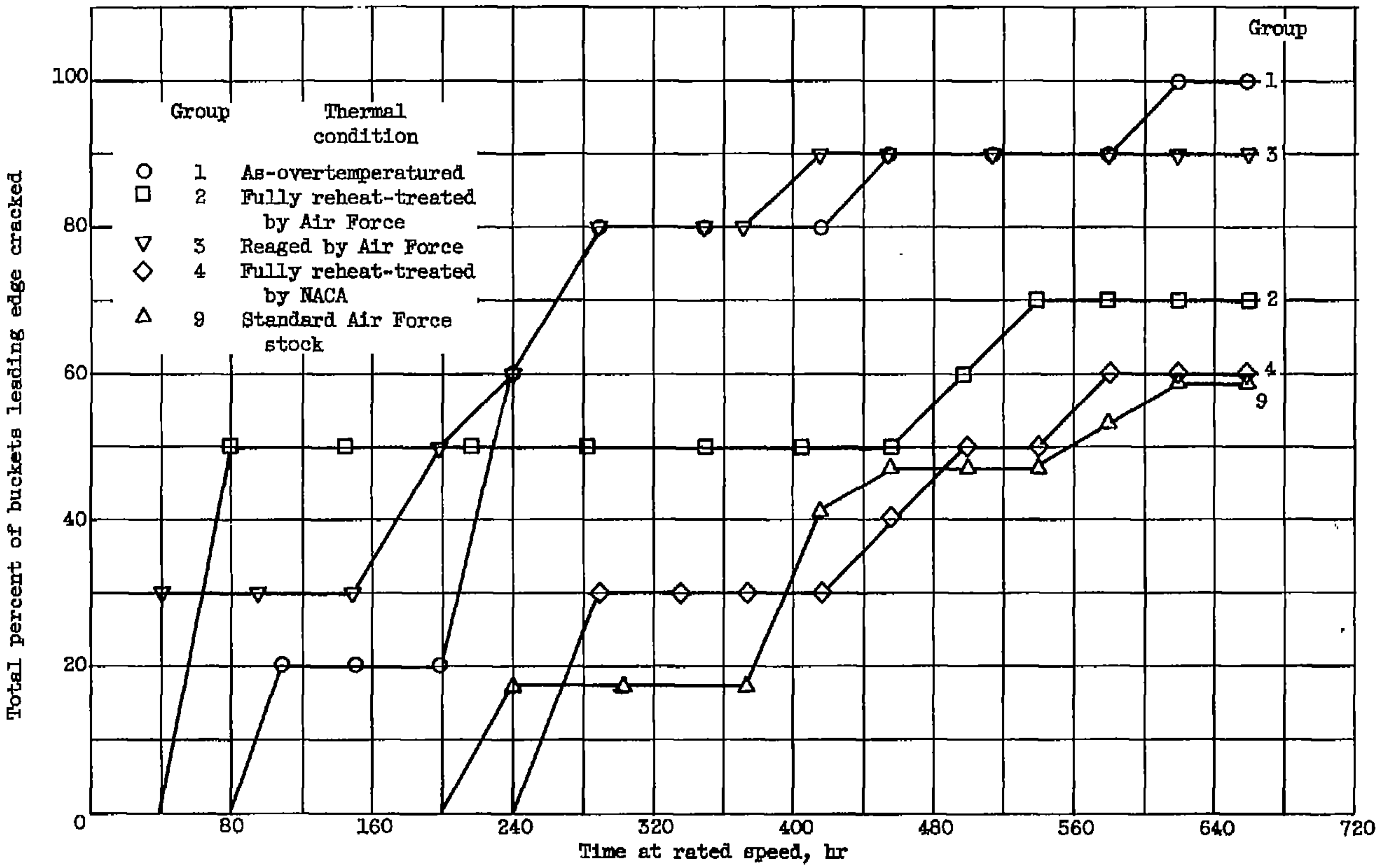
(e) Bucket fracture from a leading-edge crack after 652 hours of operation.

Figure 4. - Continued. Progression of cracks in representative buckets.

C-41976

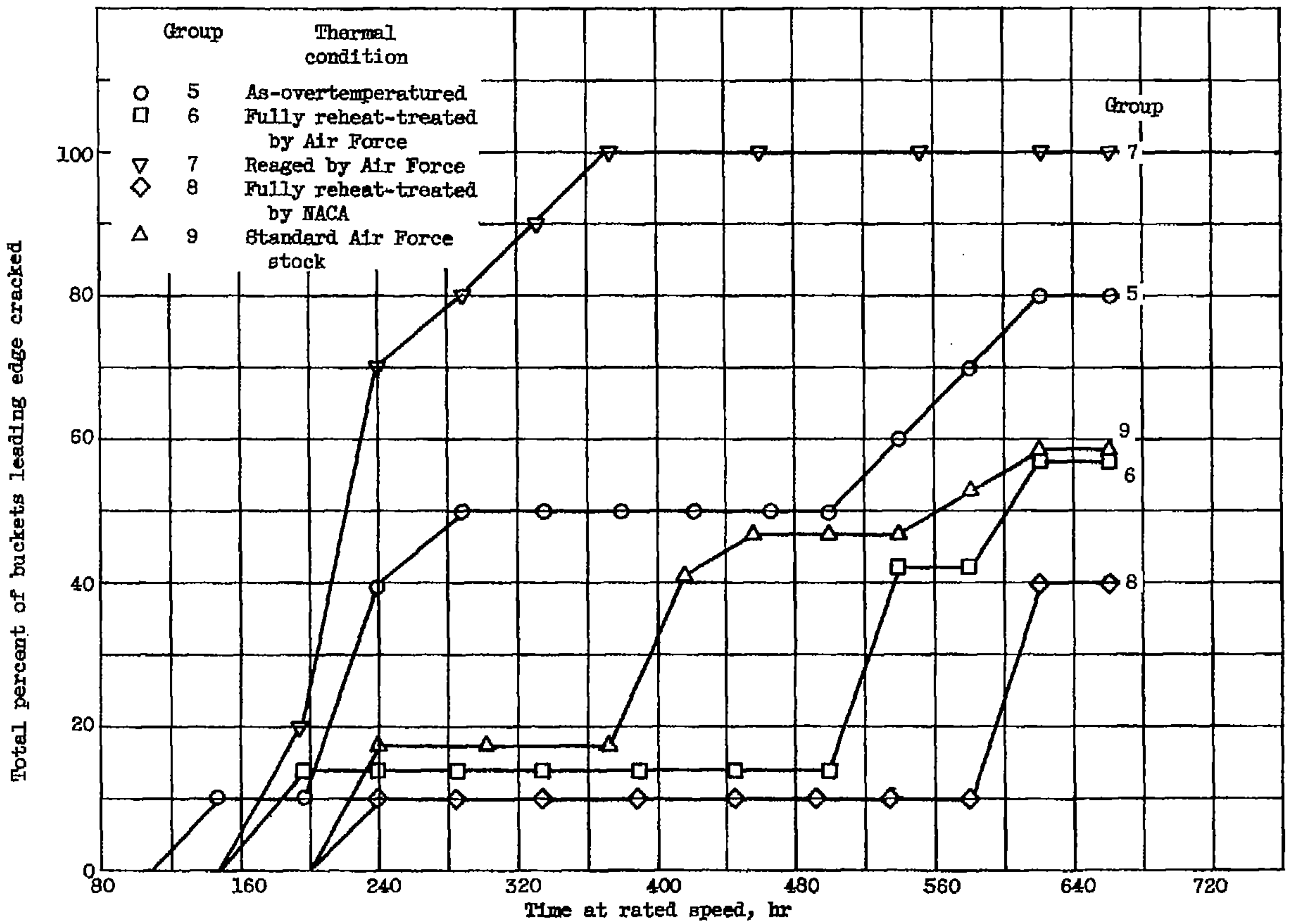
(f) Conclusion of test, 660 hours.

Figure 4. - Concluded. Progression of cracks in representative buckets.



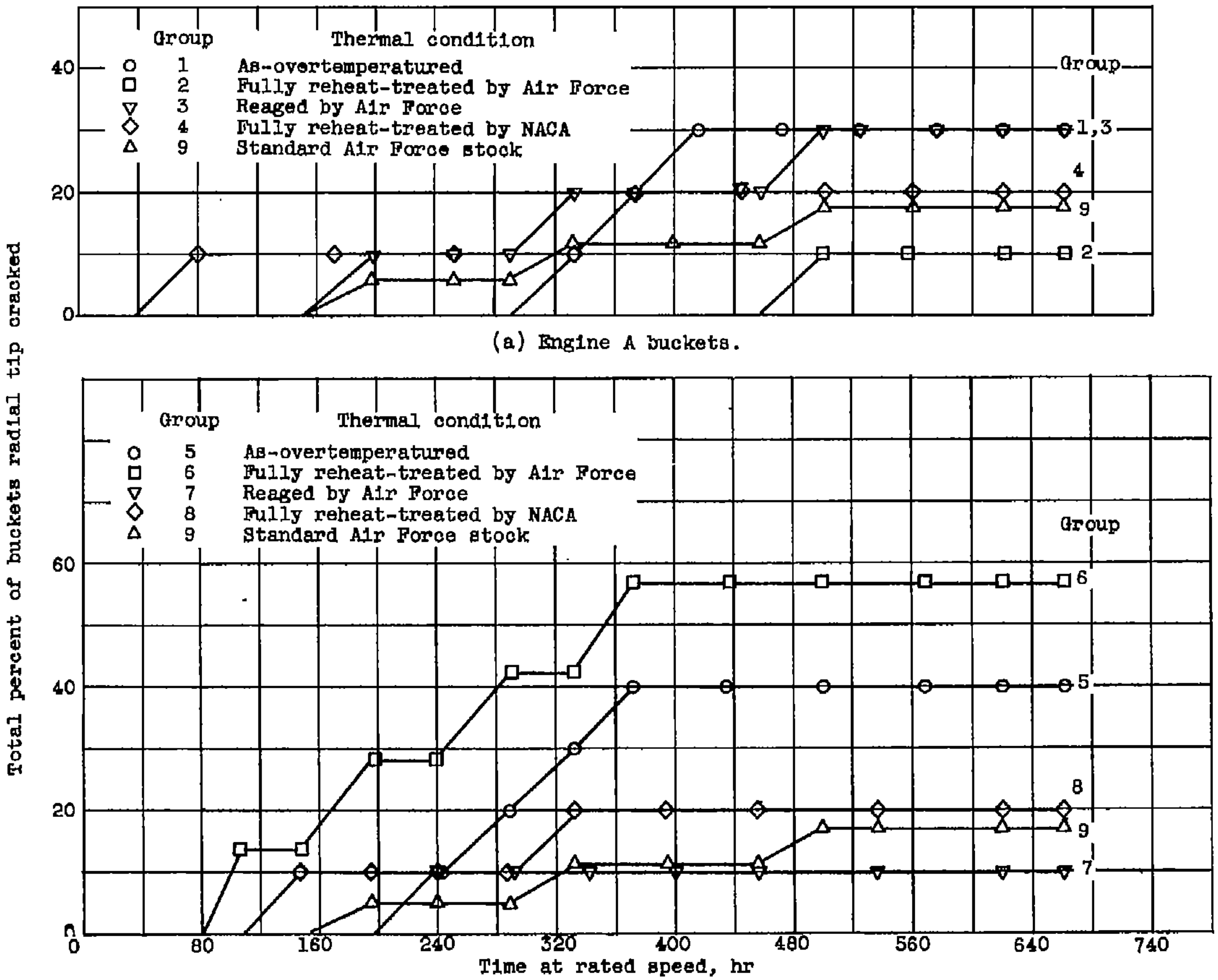
(a) Engine A buckets.

Figure 5. - Leading-edge cracking with time at rated speed.



(b) Engine B buckets.

Figure 5. - Concluded. Leading-edge cracking with time at rated speed.



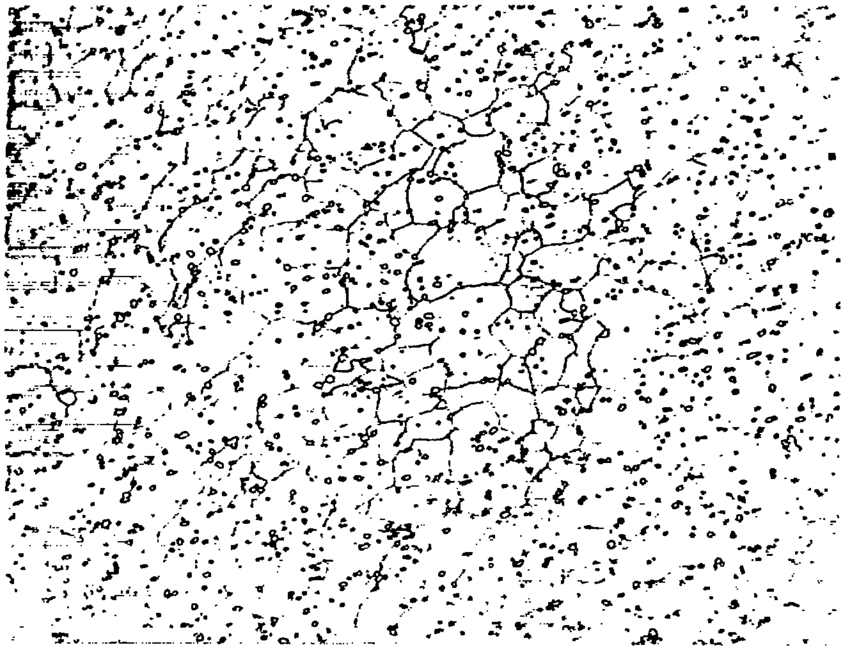
(a) Engine A buckets.

(b) Engine B buckets.

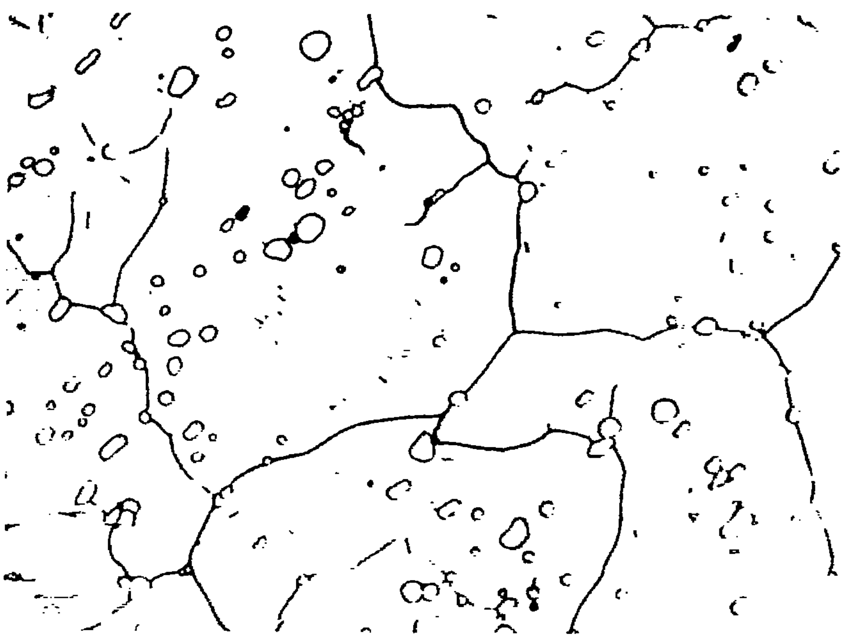
Figure 6. - Radial-tip cracking with time at rated speed.

4567

X250



X1000



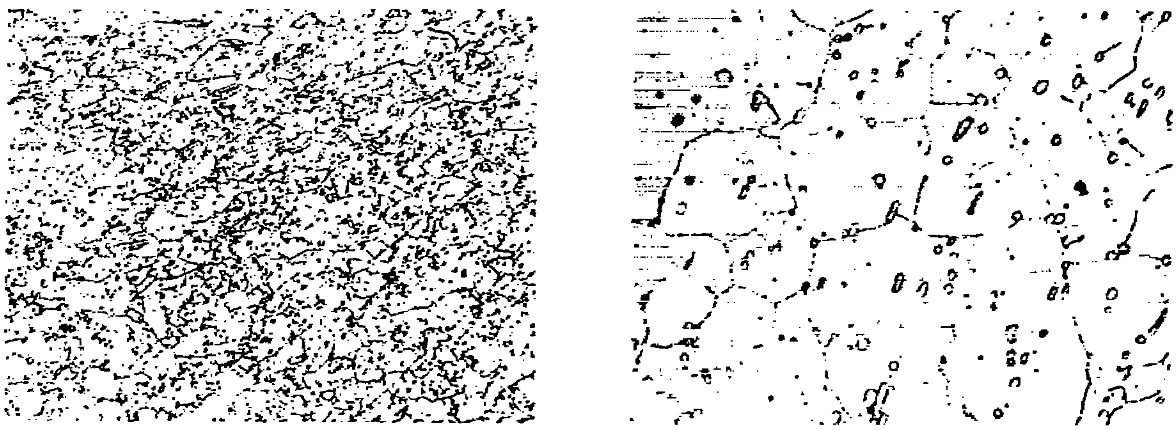
C-46927

(a) Group 9, standard S-816.

Figure 7. - Microstructures of untested buckets. Etchant, aqua regia plus glycerol.

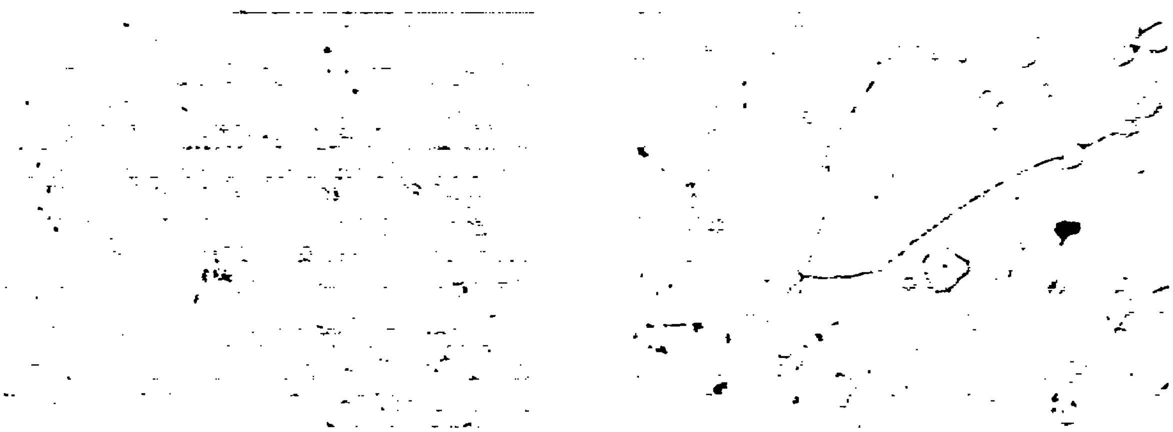
4567

X250 X1000



Group 1, overtemperatured in engine A

X250 X1000

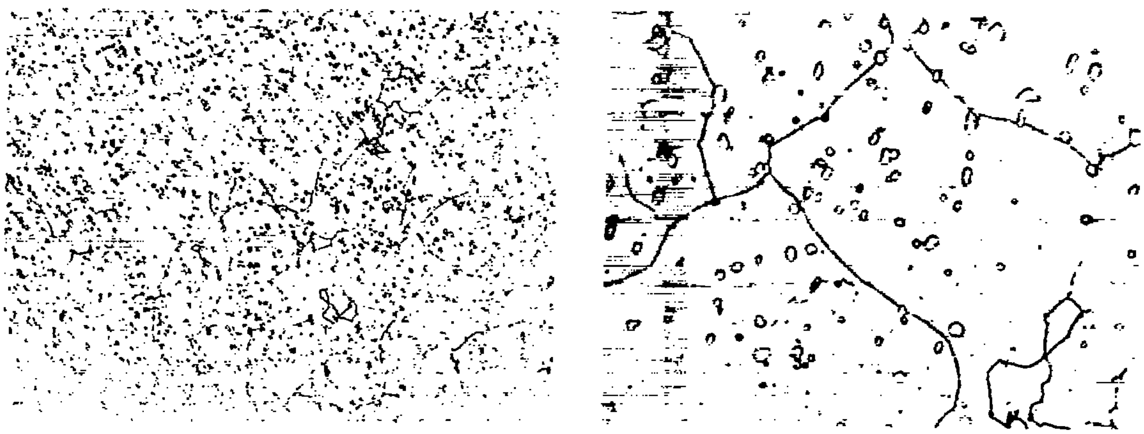


Group 5, overtemperatured in engine B C-46928

(b) As-overtemperatured buckets.

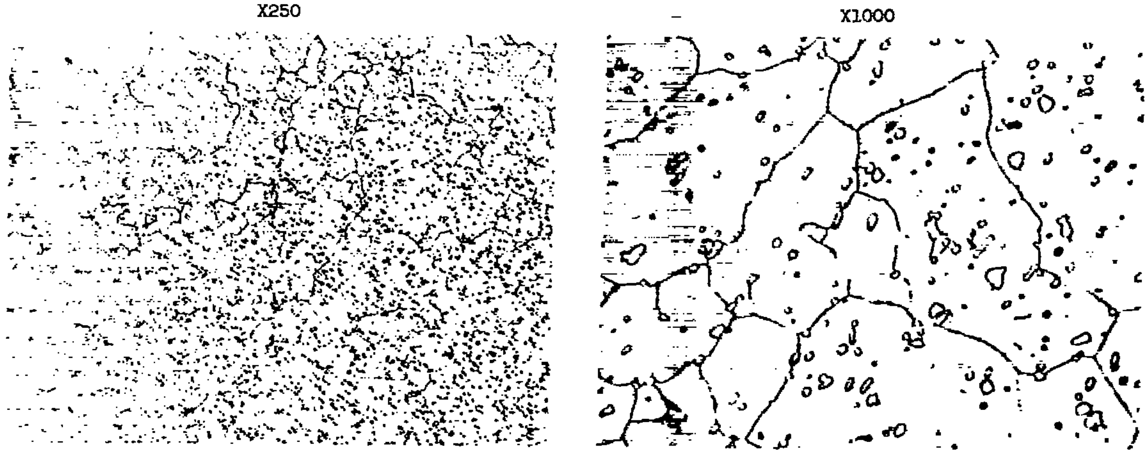
Figure 7. - Continued. Microstructures of untested buckets. Etchant, aqua regia plus glycerol.

X250 X1000



Group 2, overtemperatured in engine A and reheat-treated

X250 X1000



Group 6, overtemperatured in engine B and reheat-treated C-46929

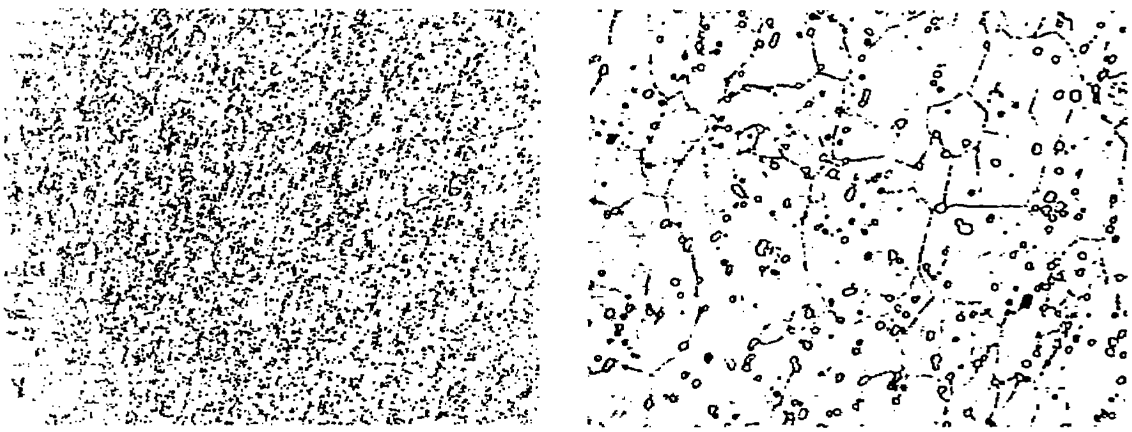
(c) Buckets overtemperatured and reheat-treated by Air Force.

Figure 7. - Continued. Microstructures of untested buckets. Etchant, aqua regia plus glycerol.

4567

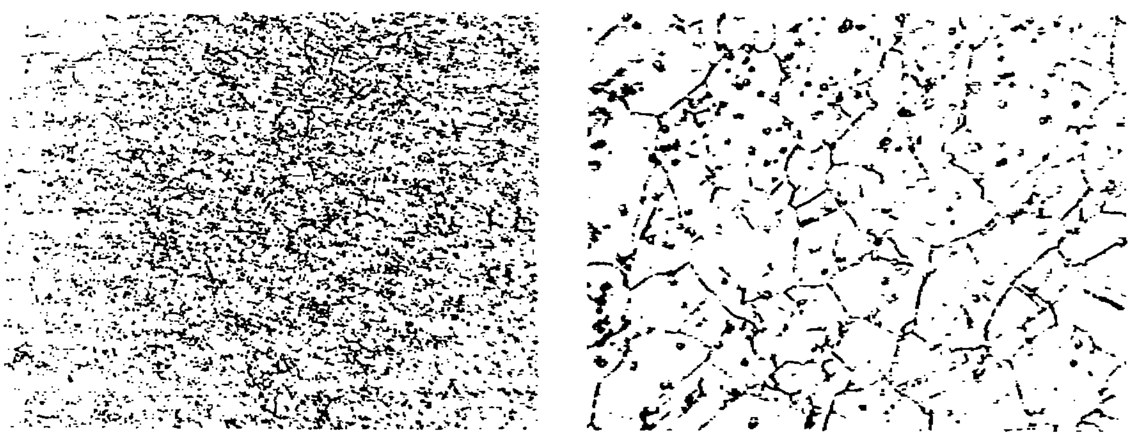
CO-5

X250 X1000



Group 3, overtemperatured in engine A and reaged.

X250 X1000



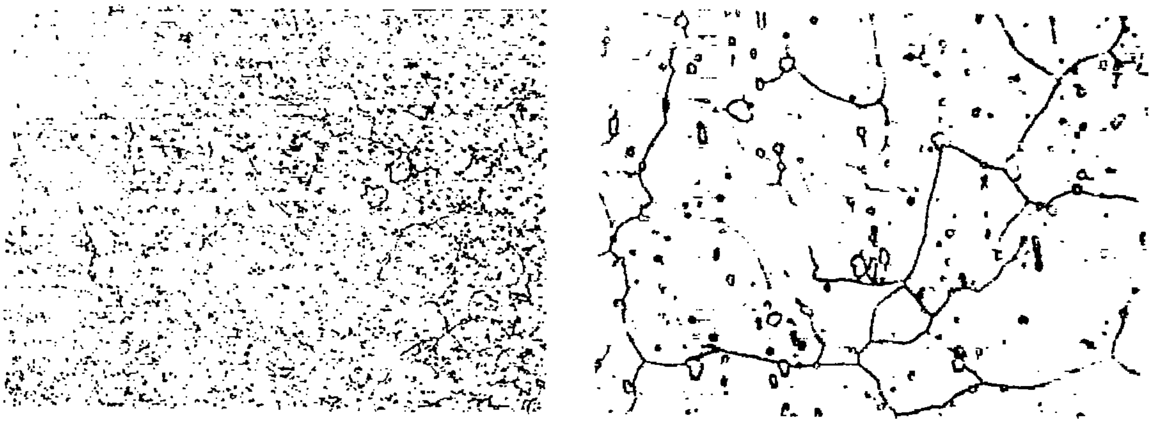
C-46930

Group 7, overtemperatured in engine B and reaged

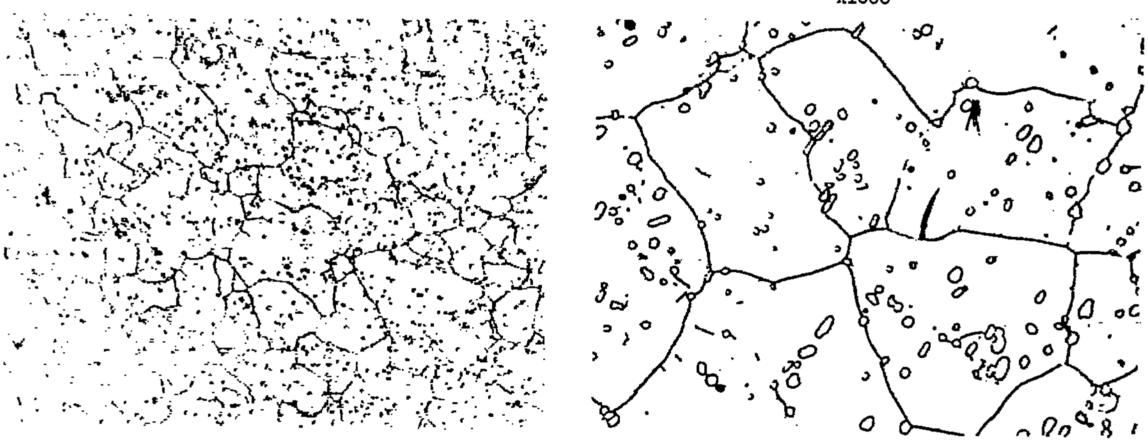
(d) Buckets overtemperatured and reaged by Air Force.

Figure 7. - Continued. Microstructures of untested buckets. Etchant, aqua regia plus glycerol.

4567



Group 4, overtemperatured in engine A and reheat-treated



Group 8, overtemperatured in engine B and reheat-treated C-46931

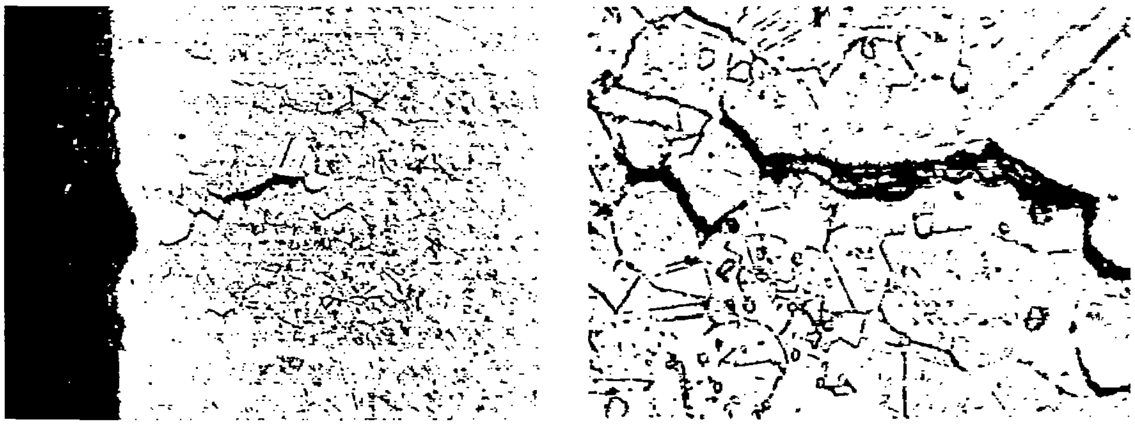
(e) Buckets overtemperatured and reheat-treated at NACA.

Figure 7. - Concluded. Microstructures of untested buckets. Etchant, aqua regia plus glycerol.

4567

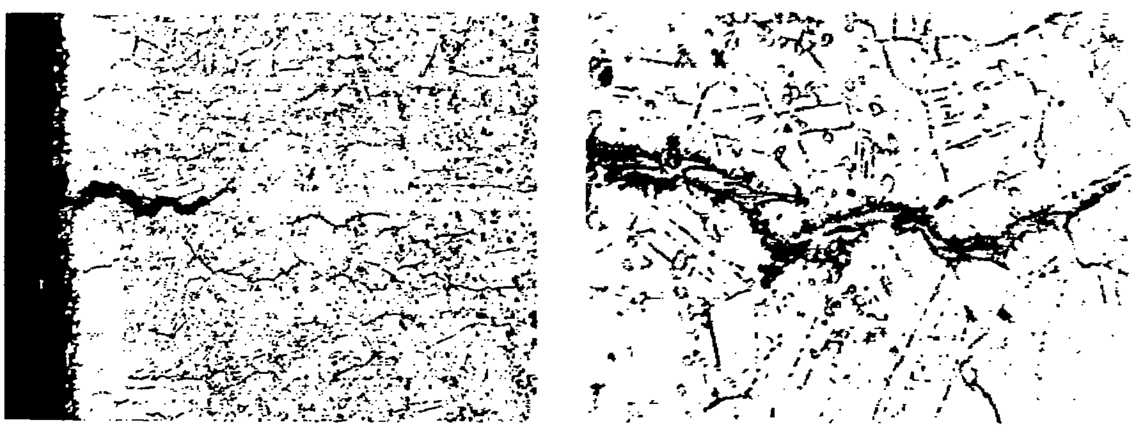
CO-5 back

X250 X1000



Group 1, overtemperatured in engine A

X250 X1000



Group 5, overtemperatured in engine B

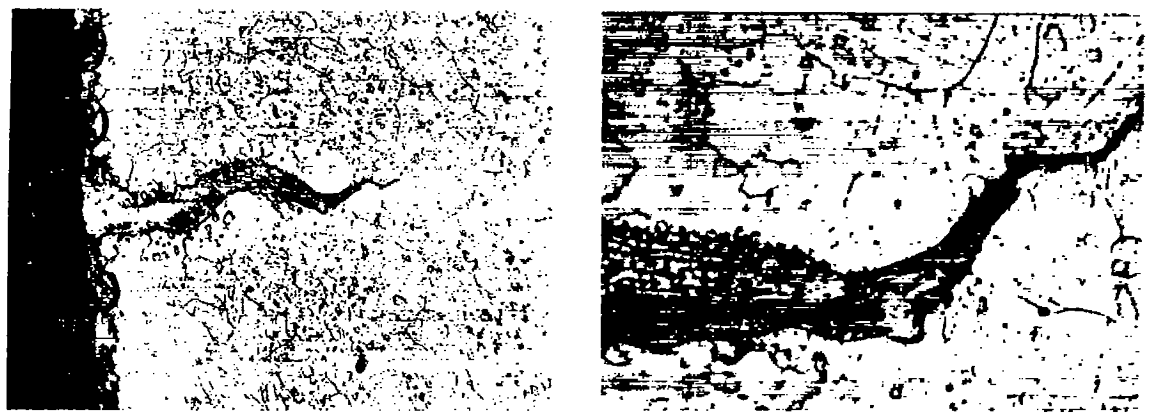
C-46932

(a) As-overtemperatured buckets.

Figure 8. - Microstructures after engine test.

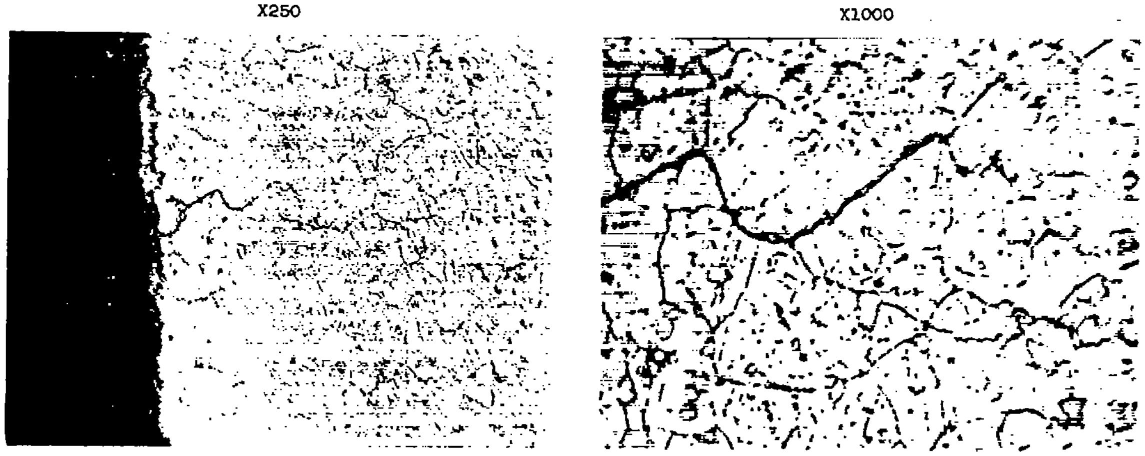
4567

X250 X1000



Group 2, overtemperatured in engine A and reheat-treated

X250 X1000

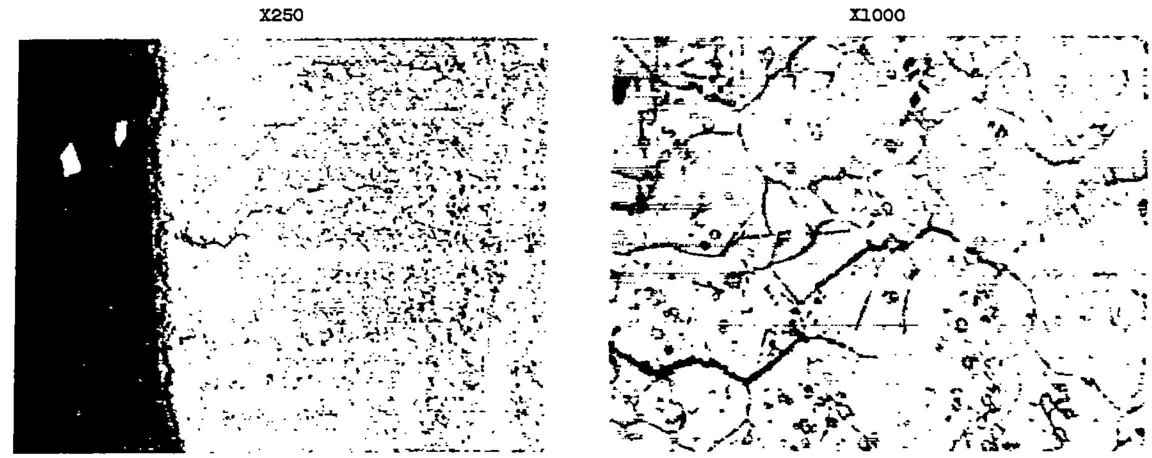


Group 6, overtemperatured in engine B and reheat-treated C-46933

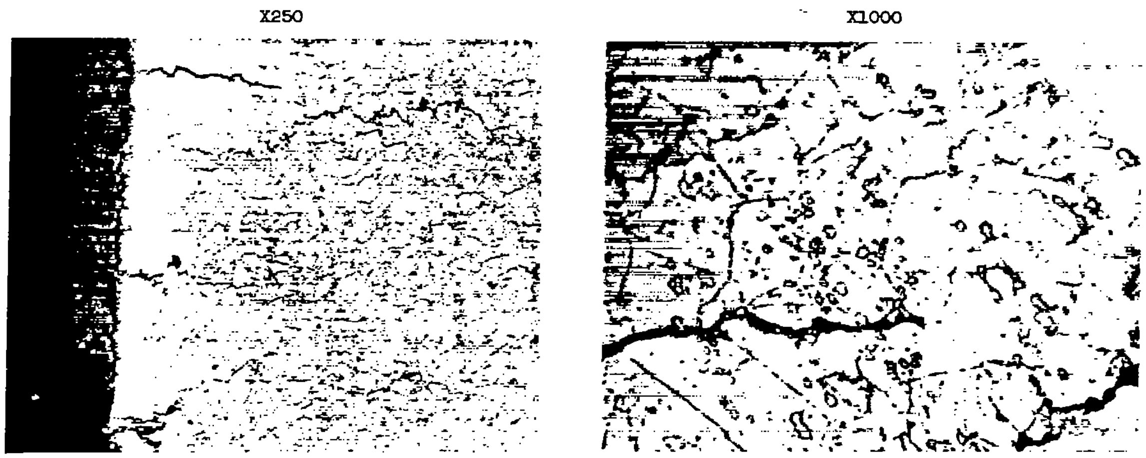
(b) Buckets overtemperatured and reheat-treated by Air Force.

Figure 8. - Continued. Microstructures after engine test.

4567



Group 3, overtemperatured in engine A and reaged



Group 7, overtemperatured in engine B and reaged

C-46934

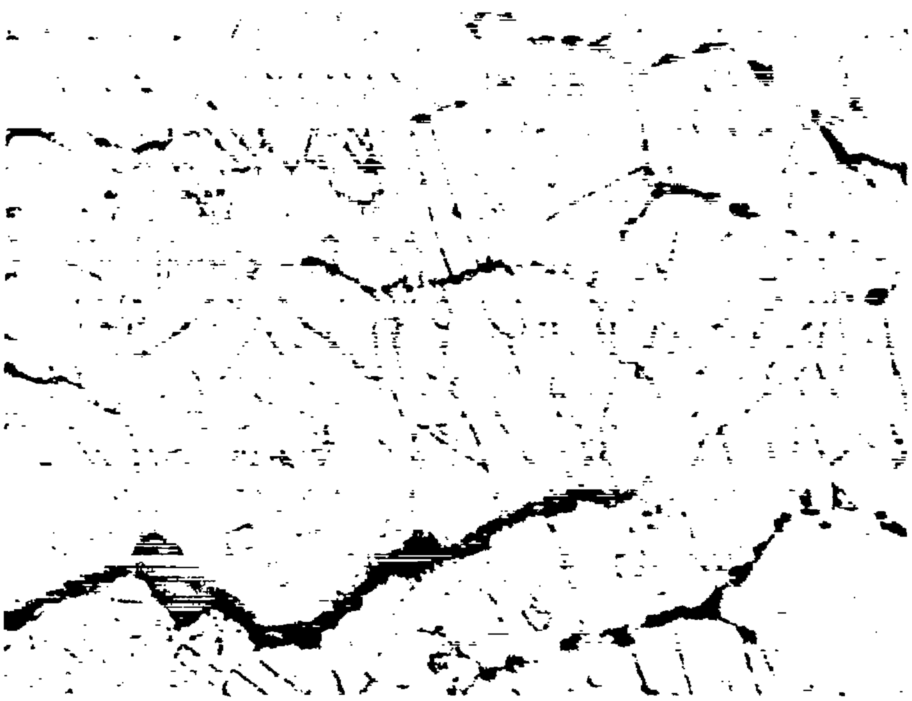
(c) Buckets overtemperatured and reaged by Air Force.

Figure 8. - Continued. Microstructures after engine test.

4567

X250

X1000



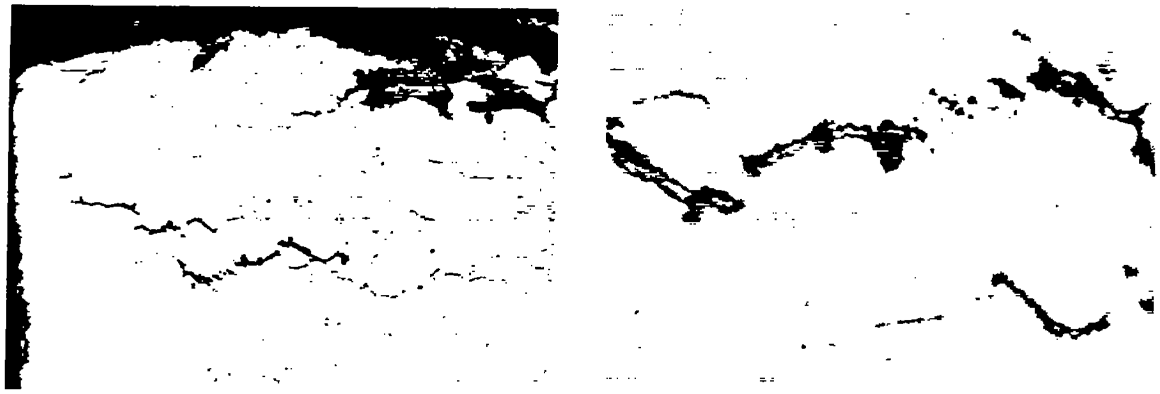
C-46935

(d) Group 9, standard S-816.

Figure 8. - Concluded. Microstructures after engine test.

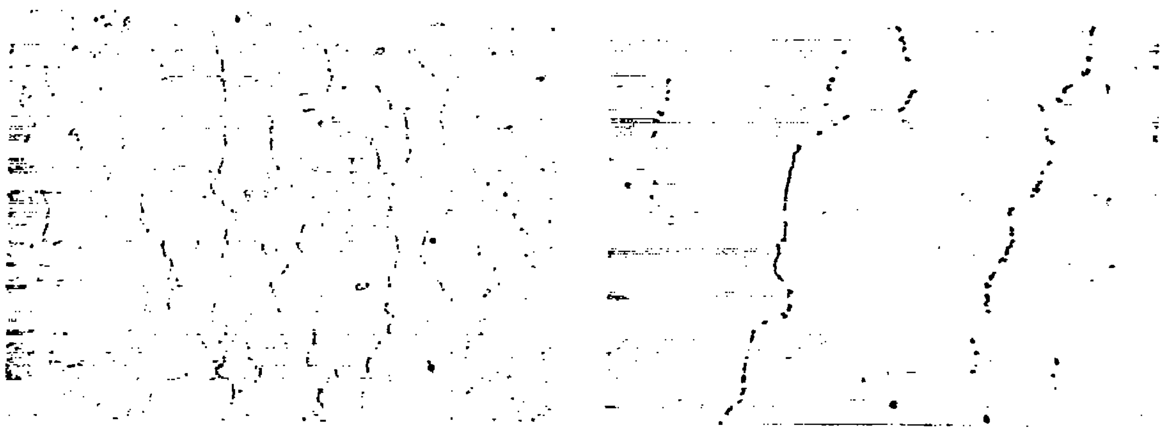
4567

X250 X750



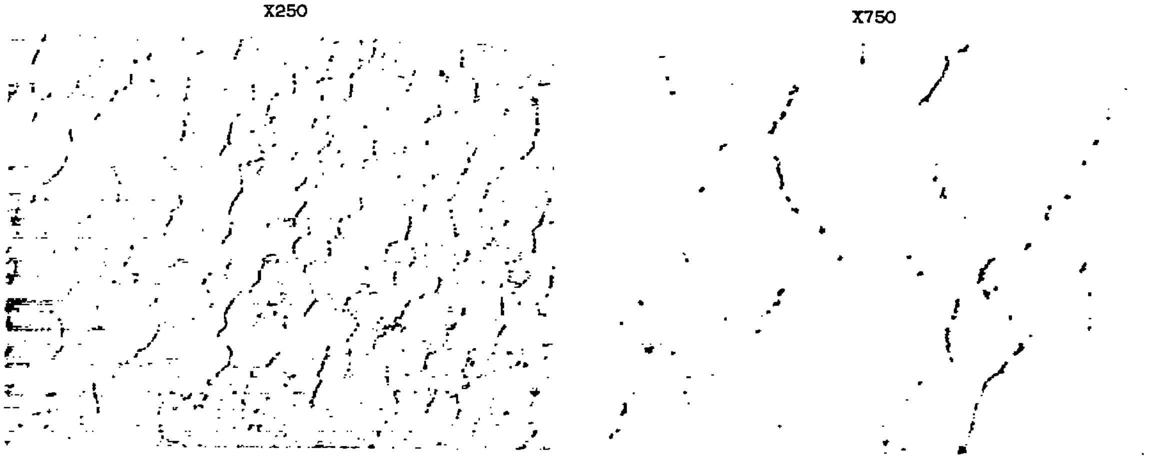
(a) As-overtemperatured.

X250 X750



(b) As-overtemperatured.

X250 X750



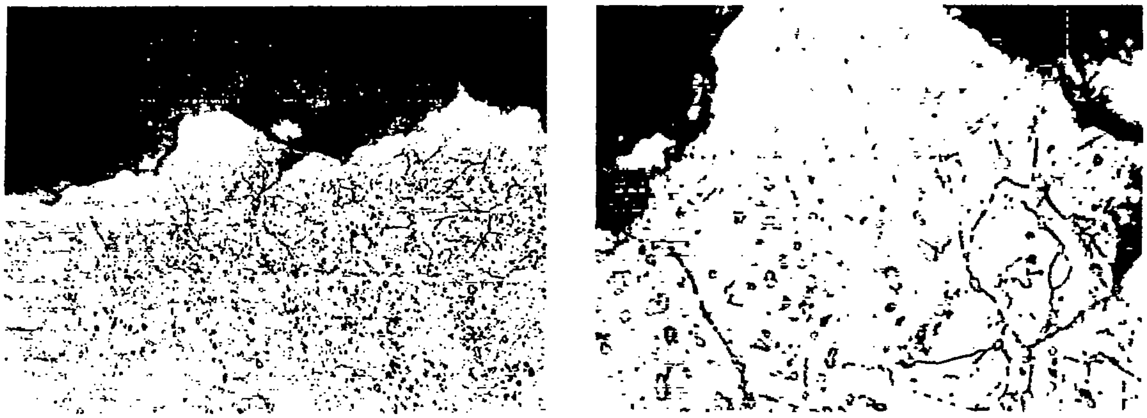
(c) Standard S-816.

C-46936

Figure 9. - Voids in as-overtemperatured and standard S-816 buckets after 660 hours at rated speed (unetched).

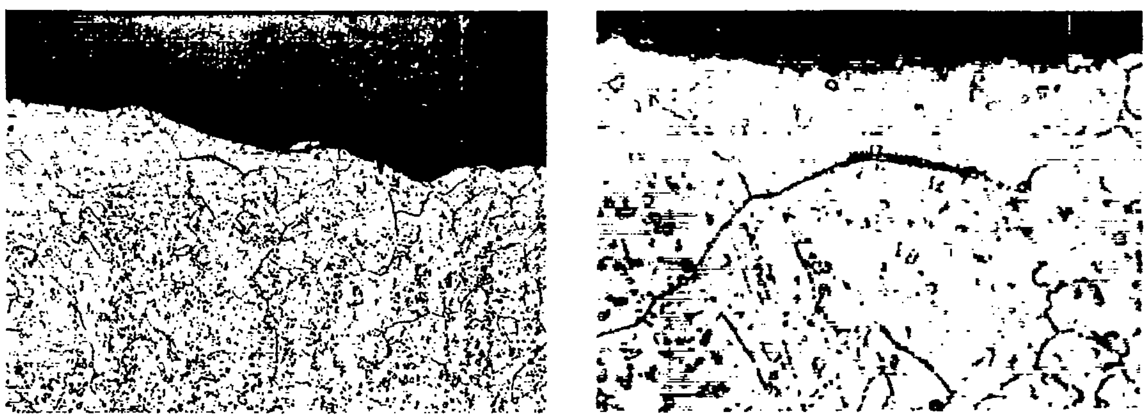
4567

X250 X750



Intergranular near leading edge of bucket

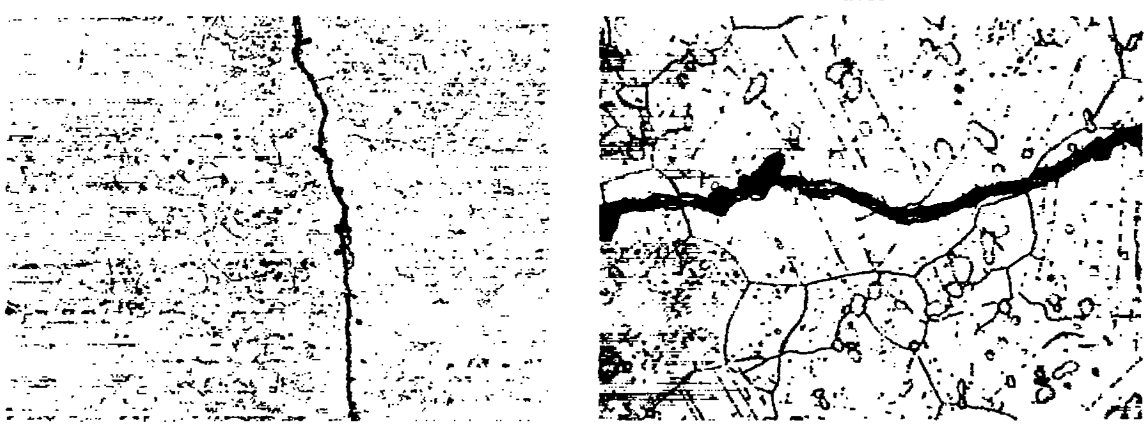
X250 X750



Transgranular portion of fracture surface following above

(a) Bucket failure progressing from leading-edge crack.

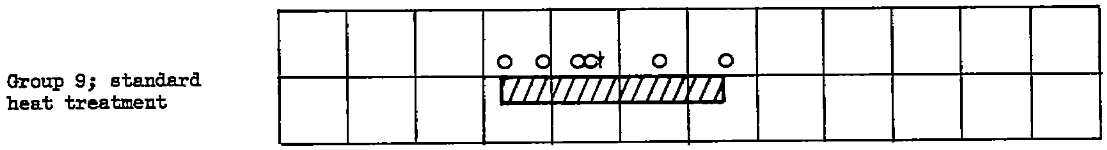
X250 X750



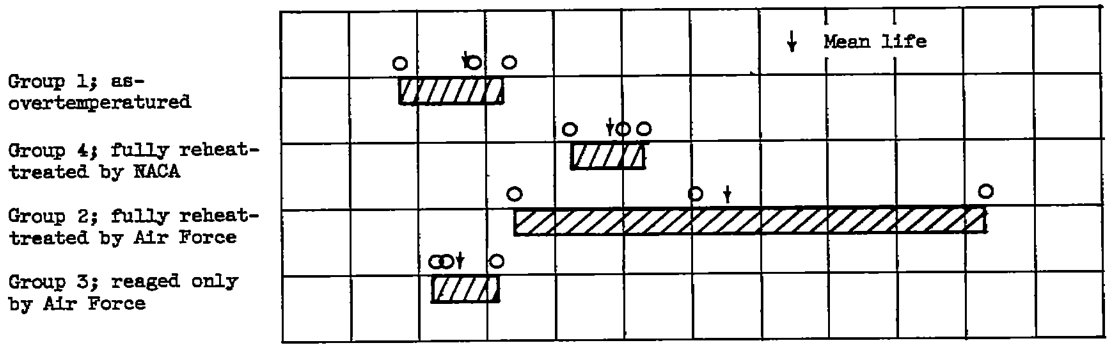
C-46937

(b) Radial tip crack.

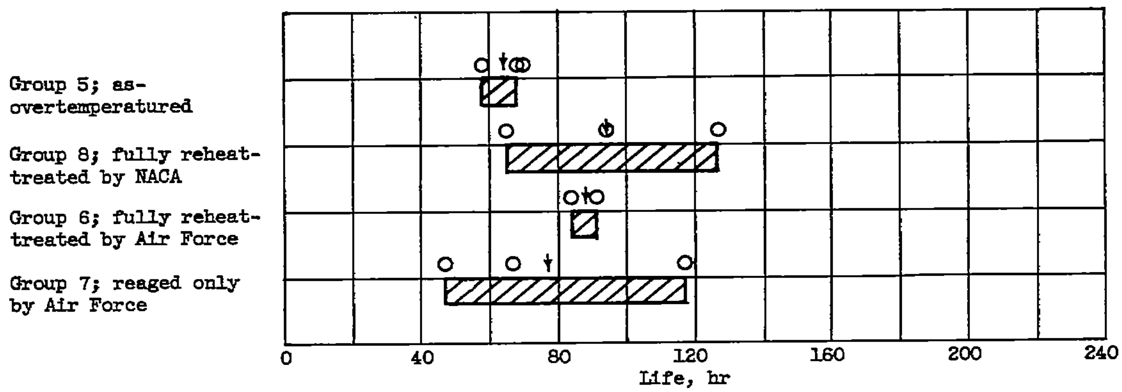
Figure 10. - Fracture surface of failed bucket and radial tip crack.



(a) Standard S-816 alloy Air Force stock.



(b) Engine A. Temperature, over 1800° F (tailpipe) on acceleration.



(c) Engine B. Temperature, over 1500° F (tailpipe); engine overspeed, 104 percent.

Figure 11. - Stress-rupture results of specimens from bucket airfoils. Stress, 23,600 pounds per square inch; temperature, 1500° F.